EXPERIMENTAL REVIEW ON PENTAQUARKS

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Abstract

The experimental evidence for pentaquarks is reviewed and compared with the experiments that do not see any sign of pentaquarks. This paper is based on a lecture given at the 33rd ITEP Winter School of Physics in the beginning of 2005. Results obtained since then are summarized in the epilogue.

1 Introduction

In the quark model, mesons are bound states of a quark and an anti-quark ($\bar{q}q$), while baryons are bound states of three quarks (qqq). The quark model successfully explains the spectrum of known hadrons. In addition to ordinary mesons and baryons QCD predicts existence of exotic states, such as glueballs (gg, ggg), hybrid mesons ($\bar{q}gq$) and multiquark states ($qq\bar{q}\bar{q}$, $qqqq\bar{q}$, $qqq\bar{q}\bar{q}\bar{q}$, $qqqqqq$, ...). Such exotic states were searched for experimentally since 60s, but no unambiguous candidates were found. Experimental evidence for the Θ^+ pentaquark in 2003 became a sensation.

2 Theoretical aspects of the Θ^+ pentaquark

The Θ^+ has a minimal quark content of $uudd\bar{s}$ and is the lightest member of an untidecuplet of pentaquarks (see Fig. 1) which was predicted in the chiral soliton model [1]. In 1987 Prashalovicz showed that the mass of the

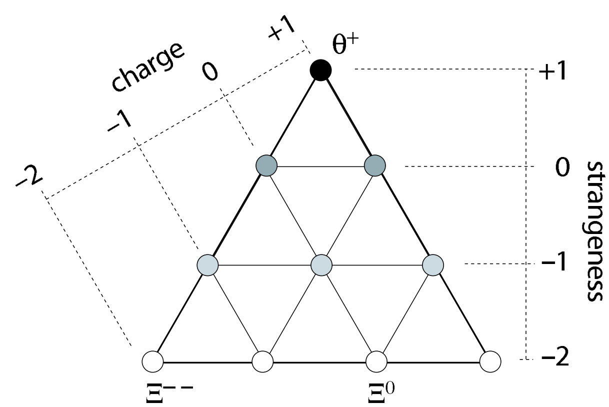

Figure 1: *The predicted anti-decuplet of pentaquark baryons. Experimental evidence for three indicated particles has been presented.*

lightest member of the antidecuplet is about $M = 1530\,\mathrm{MeV}/c^2$ [2]. In 1997 Diakonov, Petrov and Polyakov (DPP) predicted a narrow width for this state, $\Gamma < 15\,\mathrm{MeV}$ [3]. Narrow width is the result of the cancellation of leading order and two subsequent orders in the $1/N_c$ expansion. The DPP motivated the experimental search for the narrow pentaquark, and it was found in 2003 with the mass $M = 1540\,\mathrm{MeV}/c^2$ [4, 5] and the width $\Gamma \leq 1\,\mathrm{MeV}$ [6]. This width is extremely small for the state, which decays strongly in a S- or P-wave and is about 100 MeV above the threshold.

The sensitivity of the Θ^+ mass prediction to the input data was studied by Ellis, Karliner and Praszalovich [7]. They found that the prediction has a rather large uncertainty and the actual range of the possible Θ^+ masses is $1430 < M < 1660\,\mathrm{MeV}/c^2$. The ability of the chiral soliton model to explain the small width of the Θ^+ is questioned [8].

The quark model predicts rather high values for pentaquark masses [9]. It was attempted to explain the low mass of the Θ^+ by considering strong correlations between quarks. According to Jaffe and Wilczek [10] (Karliner and Lipkin [11]), the Θ^+ is a combination of two diquarks and an anti-quark (diquark and triquark). It was assumed that the correlations can considerably decrease the mass of the pentaquarks. The low width of the Θ^+ is explained by a low overlap of the wave functions of the pentaquark and final KN state, or by the mixing of two nearly degenerate in mass states [12]. In several recent calculation it was attempted to find precise states of the 5-quark systems [13, 14, 15]. However, the mass values in all the calculations were too high. Some calculations predicted other light states, which were not experimentally observed.

Both chiral soliton model and quark model with correlated quarks predict positive parity for the Θ^+. The QCD sum rules and Lattice QCD, on the other hand, predict negative parity for the Θ^+ [16, 17]. The conclusion of the Lattice QCD is controversial at the moment, some studies report evidence for the Θ^+, while in most studies no low-lying narrow pentaquarks are found. In one of the recent calculations it is shown that there exist signals of low-lying resonances, but all of them correspond to KN scattering states [18].

To summarize, there is no natural explanation of the Θ^+ properties in any of the theoretical approaches. Theory is unable to explain its low mass and narrow width. The predictions for the parity in different approaches are controversial.

3 Observation of the Θ^+

Observations of a pentaquark state Θ^+ in nK^+ [4] and pK^0 [5] modes created a lot of excitement. The corresponding invariant mass distributions obtained by the LEPS and DIANA Collaborations are shown in Figs 2 , 3.

The minimal quark content of the Θ^+ is $uudd\bar{s}$. Thus for the first time unambiguous evidence was obtained for hadrons with an additional quark–antiquark pair.

Analysis of the DIANA data demonstrates that the width of the Θ^+ is very small $\Gamma = 0.9 \pm 0.3$ MeV [6]. A similar small width was obtained from the analysis of the K^+d cross section [19) – 23]. Such a narrow width is extremely unusual for hadronic decays and requires reassessment of our understanding of

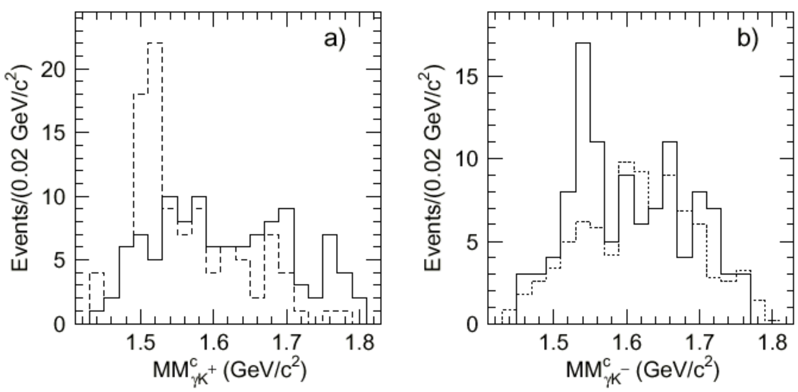

Figure 2: *Missing mass spectra for the γK^+ (left) and γK^- (right) for the reaction $\gamma C \to K^+K^-X$* [4]*. The dashed (solid) histogram shows events with (without) additional detected proton. The $\Lambda(1520)$ signal is seen on the left and evidence for Θ^+ is seen on the right.*

quark dynamics. Properties of the Θ^+ were in the excellent agreement with the theoretical predictions [3] based on the chiral quark soliton model. This paper motivated both experimental searches although later on the accuracy of these predictions was questioned [7]. In the quark soliton model the Θ^+ belongs to an antidecuplet of baryons (see Fig. 1). Octet, decuplet, 27-plet, and 35-plet of pentaquarks are also expected.

Many experiments promptly confirmed the existence of the Θ^+ [24] – [37] in different processes: photoproduction, deep inelastic scattering, hadroproduction, and neutrino interactions. Table 1 shows properties of the observed peaks.

There is some spread in the mass values obtained by different experiments. In particular masses in the pK_S final state are lower than in the nK^+ one. The accuracy of the mass determination is not high in most of the experiments and therefore the disagreement is not very serious statistically. However the DIANA and ZEUS measurements are quite precise and contradict each other by more than 4 sigma. Several experiments observe finite width of the Θ^+ that is much larger than 1 MeV. However, the accuracy is again not high and within 3 sigma all width measurements are consistent with the instrumental resolution.

The spread in mass and width may indicate that some experiments observe not a signal but a statistical fluctuation.

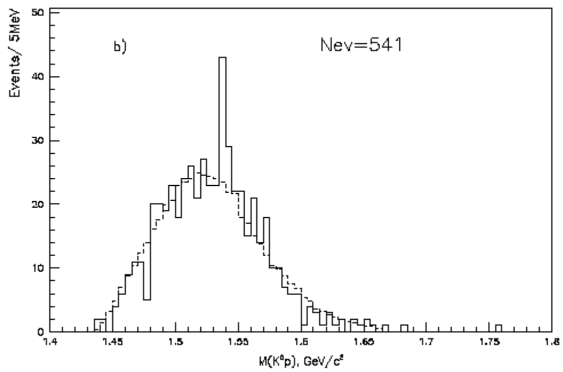

Figure 3: *Invariant mass of* pK^0 *in the reaction* $K^+Xe \rightarrow pK_SX$ [5]. *The dashed histogram is the expected background.*

If the pentaquark interpretation of observed peaks is correct one expects many other exotic (or cripto exotic) baryons belonging to the same antidecuplet or other multiplets. Indeed several experiments observe additional peaks in the vicinity of the Θ^+ mass [33, 35, 37]. For example three peaks with the estimated statistical significance of 7.1, 5.0, and 4.5 σ are seen in neutrino interactions [33].

The NA49 Collaboration claims an observation of a double strange pentaquark [38]. Two observed narrow resonances $\Xi^{--}_{\overline{10}}$ and $\Xi^{0}_{\overline{10}}$ (see Fig. 4) fit naturally into the same antidecuplet as the Θ^+ (see Fig. 1).

An evidence for an anti-charmed pentaquark was obtained by the H1 Collaboration [39] (see Fig. 5).

4 Reliability of pentaquark observations

The evidence for pentaquarks was criticized by several authors (for a review see [40]). They considered kinematic reflections, ghost tracks and arbitrary selection criteria as possible explanations for the observed peaks. The first two worries were shown to be not important at least in some experiments (for a review see [41]). The last point is especially serious since statistical significance of the positive experiments is not high and thus they are vulnerable to a psychological bias. This problem is illustrated by the JINR analysis [35] in which authors without any reason discard the momentum range where they do not see the signal. The ZUES Collaboration does not see the signal in data with $Q^2 < 20$ GeV^2. Their justification for discarding these data is also not too convincing. There are other examples of experiments with not well justified cuts. On the other hand there are experiments (for example DIANA) in which

Table 1: *Experiments with evidence for the* Θ^+ *baryon.*

Reference	Group	Reaction	Mass (MeV)	Width (MeV)
4)	LEPS(1)	$\gamma C \to K^+K^-X$	1540 ± 10	< 25
5)	DIANA	$K^+Xe \to K^0pX$	1539 ± 2	< 9
24)	CLAS(d)	$\gamma d \to K^+K^-p(n)$	1542 ± 5	< 21
25)	SAPHIR	$\gamma d \to K^+\overline{K^0}(n)$	1540 ± 6	< 25
26)	νBC	$\nu A \to K^0_s pX$	1533 ± 5	< 20
27)	CLAS	$\gamma p \to \pi^+K^+K^-(n)$	1555 ± 10	< 26
28)	HERMES	$e^+d \to K^0_S pX$	1526 ± 3	13 ± 9
29)	ZEUS	$e^+p \to K^0_S pX$	1522 ± 3	8 ± 4
30)	COSY-TOF	$pp \to K^0p\Sigma^+$	1530 ± 5	< 18
31)	SVD	$pA \to K^0_S pX$	1526 ± 5	< 24
32)	LEPS(2)	$\gamma d \to K^+K^-X$	~ 1530	
33)	$\nu BC2$	$\nu A \to K^0_s pX$	1532 ± 2	< 12
34)	NOMAD	$\nu A \to K^0_s pX$	1529 ± 3	< 9
35)	JINR	$p(C_3H_8) \to K^0_s pX$	1545 ± 12	16 ± 4
36)	JINR(2)	$CC \to K^0_s pX$	1532 ± 6	< 26
37)	LPI	$np \to npK^+K^-$	1541 ± 5	< 11

event selection criteria have high efficiency and reasonably justified.

The statistical significance of peaks is overestimated in all experiments since the shape of the background is not known. This looks obvious if one removes the fit curves and plot the data points with error bars (see Fig. 6 taken from [40]).

Nevertheless the number of experiments is large and the combined significance is high if we disregard for a moment the spread in the peak position and width. So one can not prove that all observed peaks are fakes or statistical fluctuations. Only high statistics experiments can confirm or disprove the claim for pentaquarks.

5 Non-observation experiments

Experiments which do not observe pentaquarks are shown in Table 2. Many of them are high statistics experiments which observe by far larger number of conventional resonances than the experiments which observe pentaquarks,

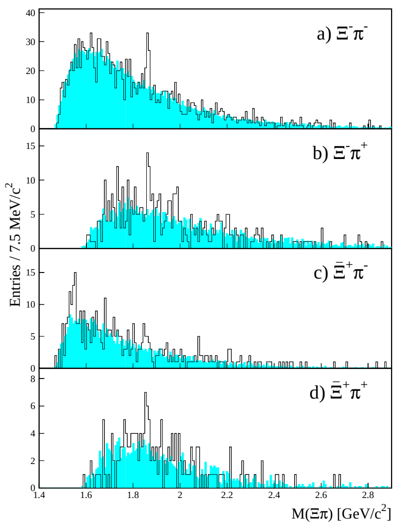

Figure 4: *Invariant mass spectra for* $\Xi^-\pi^-$ *(a),*$\Xi^-\pi^+$ *(b),*$\overline{\Xi}^+\pi^-$ *(c), and* $\overline{\Xi}^+\pi^+$ *(d) in the NA49 experiment. The shaded histograms are the normalized mixed-event backgrounds.*

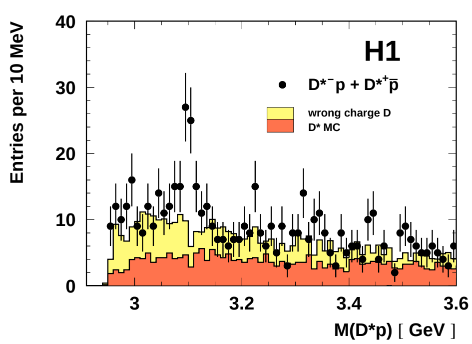

Figure 5: *Invariant mass distribution of* $D^{*-}p$ *and* $D^{*+}\overline{p}$ *combinations in the H1 experiment. Two background components are shown as the shaded histograms.*

and have much better mass resolution. The first significant negative result was published by the HERA-B Collaboration [46]. HERA-B does not see any evidence for the Θ^+ but observes a clear $\Lambda(1520)$ and $\overline{\Lambda}(1520)$ signals of about two thousand events. HERA-B obtains an upper limit on the ratio of production cross sections for the Θ^+ and $\Lambda(1520)$ of $R_{\Lambda^*} < 2.7\%$ at the 95% C.L. for

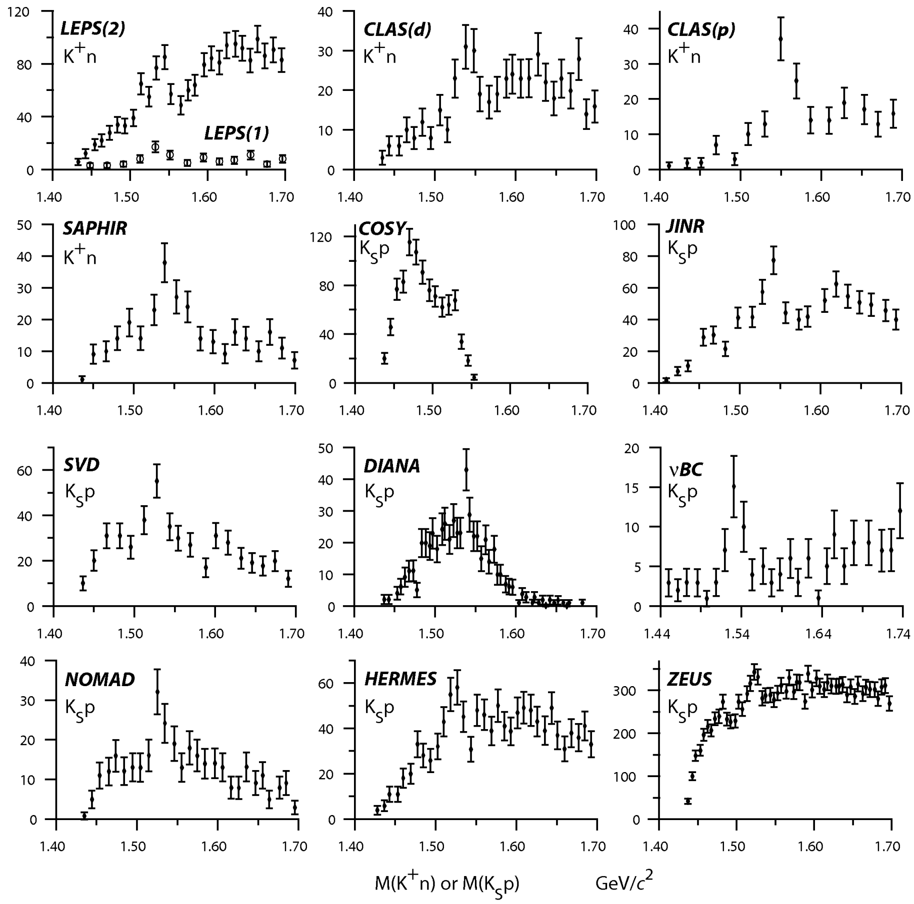

Figure 6: *Mass spectra of nK^+ and pK_S pairs in the experiments which provide evidence for the Θ^+.*

$M_{\Theta^+} = 1530$ MeV. In the whole range of reported Θ^+ masses from 1522 MeV to 1555 MeV the limit varies up to 16%.

The ratio of the Θ^+ and $\Lambda(1520)$ production cross sections R_{Λ^*} is often used for the comparison of different experiments since $\Lambda(1520)$ is narrow and easily reconstructed, it has a mass similar to the Θ^+ mass and one can draw similar diagrams for $\Lambda(1520)$ and Θ^+ production by exchanging an $\overline{K}$ meson into a K meson. The existence of similar diagrams unfortunately does not prove that production mechanisms for Θ^+ and $\Lambda(1520)$ are similar. The ratio R_{Λ^*} is of the order of unity in several experiments which observe the Θ^+ and

Table 2: *Experiments with non-observation of the Θ^+ baryon.*

Reference	Group	Reaction	Limit
42)	BES	$e^+e^- \to J/\Psi \to \bar{\Theta}\Theta$	$< 1.1 \times 10^{-5}$ B.R.
43)	BaBar	$e^+e^- \to \Upsilon(4S) \to pK^0X$	$< 1.0 \times 10^{-4}$ B.R.
44)	Belle	$e^+e^- \to B^0\bar{B}^0 \to p\bar{p}K^0X$	$< 2.3 \times 10^{-7}$ B.R.
46)	HERA-B	$pA \to K^0_S pX$	$< 0.02 \times \Lambda^*$
47)	SPHINX	$pC \to \Theta^+X$	$< 0.1 \times \Lambda^*$
48)	HyperCP	$\pi, K, pCu \to K^0_S pX$	$< 0.3\%\ K^0p$
49)	CDF	$p\bar{p} \to K^0_S pX$	$< 0.03 \times \Lambda^*$
50)	FOCUS	$\gamma BeO \to K^0_S pX$	$< 0.02 \times \Sigma^*$
51)	Belle	$\pi, K, pA \to K^0_s pX$	$< 0.02 \times \Lambda^*$
52)	PHENIX	$Au + Au \to K^-\bar{n}X$	(not given)
45)	ALEPH	$e^+e^- \to K^0_s pX$	$< 0.07 \times \Lambda^*$
53)	COMPASS	$\mu^+A \to K^0_s pX$	–
54)	DELPHI	$e^+e^- \to K^0_s pX$	$< 0.5 \times \Lambda^*$
55)	E690	$pp \to K^0_s pX$	$< 0.005 \times \Lambda^*$
56)	LASS	$K^+p \to K^+n\pi^+$	–
54)	L3	$\gamma\gamma \to K^0_s pX$	$< 0.1 \times \Lambda$

less than a few percent in many experiments which do not see Θ^+ (see Table 2).

In order to resolve this discrepancy many authors assume that the Θ^+ production drops very fast with energy and is heavily suppressed in e^+e^- annihilation. A model exists in which the Θ^+ production cross section is strongly suppressed at high energies in the fragmentation region [57]. It is not clear how reliable this model is. In any case it is not applicable for the central production for example in the HERA-B experiment where some models predict the Θ^+ yield much higher than the experimental limits [58].

However, the Θ^+ production mechanism is not known and therefore it is important to have a high statistics experiment at low energies where most evidence for pentaquarks comes from. This goal was achieved by the BELLE Collaboration which analyzed interactions of low momentum particles produced in e^+e^- interactions with the detector material. We will discuss this experiment after reviewing the situation with the anti-charmed and doubly strange pentaquarks.

6 The anti-charmed pentaquark

The anti-charmed pentaquark was observed in the pD^{*-} and $\overline{p}D^{*+}$ channels by the H1 Collaboration both in DIS and photo production [39]. After many experimental checks H1 concludes that the signal is real and self consistent. Still the signal has very unusual properties. The Θ_c^0 measured width of (12 ± 3) MeV is consistent with the experimental resolution of (7 ± 2) MeV. So its intrinsic width is very small although its mass is 151 MeV above the pD^{*-} threshold and 292 MeV above pD^- threshold. Its decay into pD^{*-} is clearly visible although naively one would expect much larger branching fraction for the pD^- channel where energy release is twice larger. Finally it is produced with an enormous cross section. About 1.5% of all charged D* mesons are coming from decays of this new particle! These properties are very surprising but we can not a priory exclude such a possibility.

However, the ZEUS experiment which works at the same electron–proton collider HERA does not see Θ_c^0 and gives an upper limit of 0.23% at the 95% C.L. on the fraction of charged D^* coming from Θ_c^0 decays [59]. We denote this fraction $R_{\Theta_c^0/D^*}$. For DIS events with $Q^2 > 1$ GeV^2 the upper limit is 0.35% at the 95% C.L. This is a clear contradiction with the H1 result. We are not aware of any convincing explanation of this discrepancy. One can try to explain the difference using following arguments. ZEUS detects more soft D^* than H1. If one assumes that pentaquarks are produced with high momenta only, than D^* mesons from their decays should be also energetic. In this case soft D^* that are more efficiently detected by ZEUS should not be used in the comparison with H1. However such an assumption does not resolve the discrepancy since ZEUS does not see the signal also in the kinematic range very similar to the H1 one.

The CDF Collaboration also does not see any sign of Θ_c^0 [49]. CDF has two orders of magnitude more reconstructed D^* mesons. They reconstruct 6247 ± 1711 $D_2^{*0} \to D^{*+}\pi^-$ and 3724 ± 899 $D_1^0 \to D^{*+}\pi^-$ decays which have the event topology very similar to Θ_c^0. Majority of charm particles at HERA and Tevatron are produced in the fragmentation process. It is impossible to reconcile the results of the two experiments if Θ_c^0 is produced in the fragmentation process as well. No other mechanism was proposed so far. There are also upper limits on Θ_c^0 production in e^+e^- collisions by ALEPH [45] and in photo production by FOCUS [50].

We conclude that the evidence for Θ_c^0 is by far weaker than the evidence against it.

7 Doubly strange pentaquark

The NA49 claim for the observation of the doubly strange pentaquark was not supported by several experiments which tried to find it. HERA-B has 8 times more Ξ^- hyperons and slightly better mass resolution. There is no $\Xi(1862)$ signal in the $\Xi^-\pi^-$ or $\Xi^-\pi^+$ mass distributions (see Fig. 7) while there is a clear $\Xi(1530)^0$ peak with about 1000 events (including charge conjugate combinations). HERA-B sets an upper limit of $4\%/B(\Xi(1862)^{--} \rightarrow \Xi^-\pi^-)$ at the 95%C.L. on the ratio of production cross section for $\Xi(1862)^{--}$ and $\Xi(1530)^0$. We denote this ratio $R_{\Xi(1862)/\Xi(1530)}$. $R_{\Xi(1862)/\Xi(1530)}$ is about $18\%/B(\Xi(1862)^{--} \rightarrow \Xi^-\pi^-)$ in the NA49 experiment [46, 60]. The center

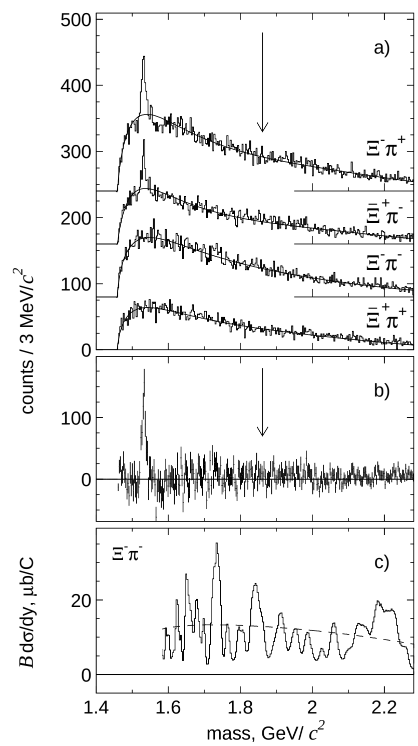

Figure 7: *The $\Xi\pi$ invariant mass spectra for $p + C$ collisions in the HERA-B experiment (a); sum of all four $\Xi\pi$ spectra with the background subtracted (b); upper limit at 95%C.L. for mid-rapidity (c) .*

of mass energy in HERA-B is about 2 times larger than in NA49. However

the arguments about a very fast drop of the pentaquark production cross section in the fragmentation region [57] do not apply to the central production where the signal is observed by NA49 [38] and where it is searched for at HERA-B. The E690 experiment has even smaller limit on the $R_{\Xi(1862)/\Xi(1530}$ of $0.2\%/B(\Xi(1862)^{--} \to \Xi^-\pi^-)$ at the 95% C.L. [55]. E690 studies proton–proton interactions at 800 GeV i.e., the same process as NA49 but at the twice larger CM energy. The WA89 experiment has about 300 times larger number of Ξ^- hyperons but does not observe $\Xi(1860)$ [61]. However this experiment uses a Σ^- beam and a straightforward comparison is not possible. The ALEPH, BaBar, CDF, COMPASS, FOCUS and ZEUS experiments also do not see $\Xi(1862)$ in a variety of initial processes [45, 43, 49, 53, 50, 59].

We conclude that the evidence for $\Xi(1862)$ is by far weaker than the evidence against it.

8 The Belle experiment

As discussed above many high statistics experiments do not see the Θ^+ and set stringent limits on its production cross section in different processes. It was argued, however, that the Θ^+ production can be suppressed at high energies or in specific processes like e^+e^- annihilation. Therefore Belle decided to study interactions of low momentum particles produced in e^+e^- interactions with the detector material. This allows to achieve production conditions similar to the experiments which observe the Θ^+ . For example the most probable kaon momentum is only 0.6 GeV (see Fig. 8). The Belle kaon momentum spectrum has a large overlap with the DIANA spectrum [5].

The analysis is performed by selecting pK^- and pK_S secondary vertices. The protons and kaons are required not to originate from the region around the run-averaged interaction point. The proton and kaon candidate are combined and the pK vertex is fitted. The xy distribution of the secondary pK^- vertices is shown in Fig. 9 for the barrel part (left) and for the endcap part (right) of the detector. The double wall beam pipe, three layers of SVD, the SVD cover and the two support cylinders of the CDC are clearly visible. The xy distribution for secondary pK_S vertices is similar.

The mass spectra for pK^- and pK_S secondary vertices are shown in Fig. 10. No significant structures are observed in the $M(pK_S)$ spectrum, while in the $M(pK^-)$ spectrum a $\Lambda(1520)$ signal is clearly visible.

The $\Lambda(1520)$ yield is 15.5 thousand events. The $\Lambda(1520)$ momentum spectrum is relatively energetic (see Fig. 11). $\Lambda(1520)$ produced in a formation channel should be contained mainly in the first bin of the histogram even in the presence of the Fermi motion. Therefore most of $\Lambda(1520)$ are produced in the production channel.

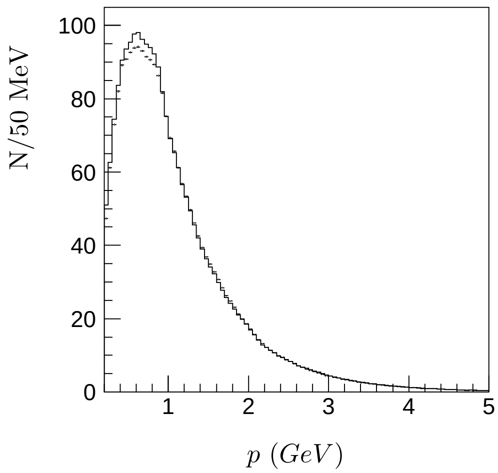

Figure 8: *Momentum spectra of K^+ (solid histogram) and K^- (dashed histogram) in the Belle experiment.*

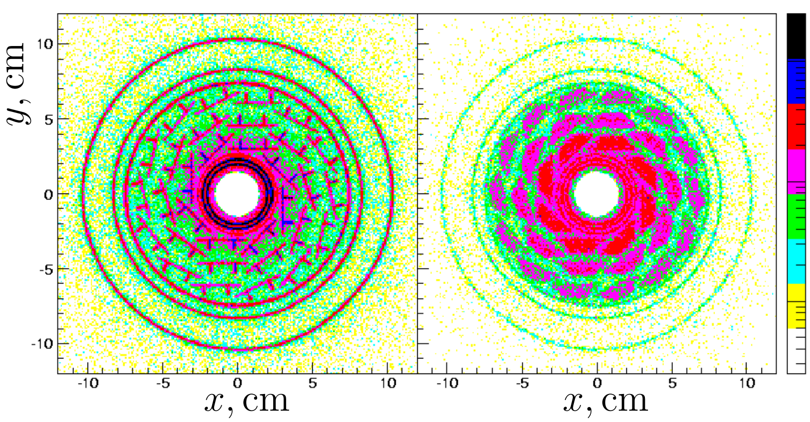

Figure 9: *The xy distribution of secondary pK^- vertices for the barrel (left) and endcap (right) parts of the Belle detector.*

The upper limit for the narrow Θ^+ yield is 94 events at the 90% C.L. for $M_{\Theta^+} = 1540$ MeV. This leads for the upper limit of 2% at the 90% C.L. on the ratio of Θ^+ and $\Lambda(1520)$ production cross sections. For other reported Θ^+ masses the limit is even smaller.

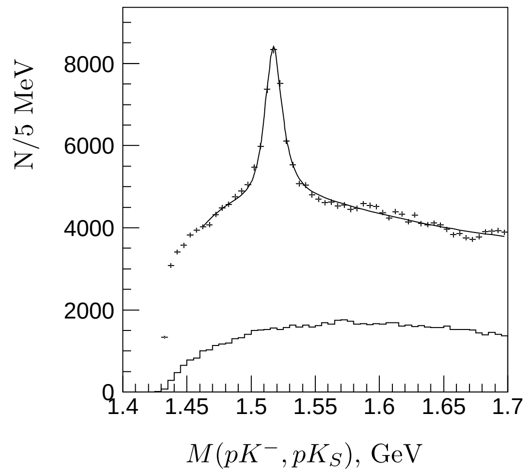

Figure 10: *Mass spectra of pK^- (points with error bars) and pK_S (histogram) secondary pairs in the Belle experiment.*

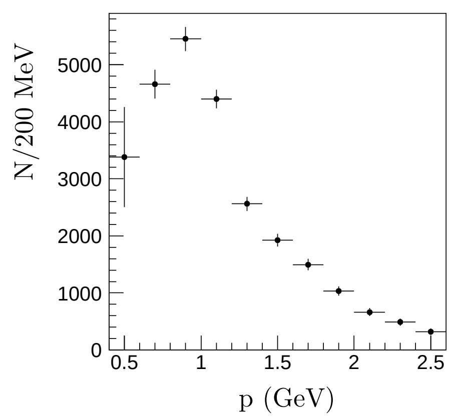

Figure 11: $\Lambda(1520)$ *momentum spectrum in the Belle experiment.*

Projectiles are not reconstructed in the Belle approach. Therefore the Θ^+ and $\Lambda(1520)$ can be produced by any particle originating from the e^+e^- annihilation: $K^\pm$, $\pi^\pm$, K^0_S, K^0_L, p, Λ, etc. Belle shows that $\Lambda(1520)$ are seldom accompanied by K^+ mesons from the same vertex. This means that $\Lambda(1520)$ are produced mainly by particles with negative strangeness. The fraction of

energetic Λ hyperons in e^+e^- annihilation is too small to dominate $\Lambda(1520)$ production.

The Belle limit is much smaller than the results reported by many experiments which observe the Θ^+. For example it is two orders of magnitude smaller than the value reported by the HERMES Collaboration [28]. The Θ^+ and $\Lambda(1520)$ are produced in inclusive photoproduction at HERMES. Photons produce hadrons dominantly via (virtual) pions or Kaons. Therefore the production conditions are quite similar in the two experiments. We do not know any physical explanation for the huge difference between the Belle and HERMES results.

The expected number of reconstructed Θ^+ in the formation reaction $K^+n \to pK^0_S$ can be estimated knowing the Θ^+ width, the number of K^+ mesons with appropriate momentum, amount of material and the reconstruction efficiency. The Θ^+ width was estimated using the DIANA data to be 0.9 ± 0.3 MeV [6]. Using this value of the Θ^+ width we estimate the number of expected Θ^+ events at Belle to be comparable with their upper limit. If so the Belle result disagrees with the DIANA observation. However we should wait for a quantitative statement from the Belle Collaboration.

A comparison of the Belle upper limit on R_{Λ^*} with the exclusive photoproduction experiments is not simple. However, it is very strange to have about two orders of magnitude difference in R_{Λ^*} since the Belle kaon (and pion) momentum spectrum is quite soft and comparable with the momentum spectrum of virtual kaons (or pions) in the low energy photoproduction experiments.

9 Conclusions

The NA49 claim for the observation of $\Xi(1862)$ pentaquarks is hard to reconcile with the results of many experiments which have up to 300 times larger statistics of usual Ξ^- and $\Xi(1530)$ hyperons and a better mass resolution. In particular E690 investigated the same production process at about twice larger CM energy and obtained hundred times lower limit on the ratio of $\Xi(1862)$ and $\Xi(1530)$ production cross sections.

The H1 claim for the anti-charmed pentaquark contradicts the ZEUS study made at almost identical conditions. CDF sets a very stringent limit on the Θ^0_c yield although they observed 178 times more D^* than H1. CDF reconstructed also about 10 thousand $D^{*0}_2 \to D^{*+}\pi^-$ and $D^0_1 \to D^{*+}\pi^-$ decays (including charge conjugate states). These decays are very similar in kinematics and efficiency to $\Theta^0_c \to pD^{*-}$ decays (the H1 signal is observed mainly with energetic protons for which the particle identification does not play an important role). Three other experiments do not see any sign of the Θ^0_c in different production processes [45, 44, 50]. It is hard to reconcile the H1 claim with this overwhelming negative evidence.

The claims for observation of the Θ^+ in inclusive production at medium and high energies are not supported by many high statistics experiments which reconstruct by far larger number of ordinary hyperons with negative strangeness. Even if one assumes that the Θ^+ production is strongly suppressed at high energies there is still a contradiction between several of these results with the Belle upper limit obtained with low momentum kaons.

However, even if some claims for the Θ^+ observation are wrong it does not mean that all observations are wrong. The DIANA and exclusive photoproduction experiments are not in contradiction with the high energy experiments if one assumes that the Θ^+ production drops very fast with the energy. There is a qualitative disagreement of these experiments with the Belle data. However here we should wait for the quantitative analysis of the Belle data. Results of high statistics exclusive photoproduction experiments are expected very soon. We hope that the situation with the pentaquark existence will be clarified already this year.

10 Epilogue

This paper is based on a lecture given at the 33rd ITEP Winter School of Physics in the beginning of 2005. Instead of updating the whole text we left it unchanged in order to allow a comparison of the situation two years ago with the present knowledge. The most important new results are reviewed here.

A second generation of dedicated experiments, optimized for the pentaquark search, was undertaken at Jefferson Lab. These photoproduction experiments cover the few-GeV beam energy range where most of the positive evidence were reported. Each experiment collected at least an order of magnitude more statistics than any of the previous measurements. No positive evidence of the Θ^+ production was reported, while two negative results were published by the CLAS Collaboration [62, 63].

The CLAS Collaboration basically repeated the study of the exclusive reaction $\gamma p \to K^0 K^+ n$ [62] which was performed by the SAPHIR Group [25]. Whereas SAPHIR had reported a $4.8\,\sigma$ significant $\Theta^+ \to nK^+$ signal, no signal was found by CLAS. The upper limit on the ratio of Θ^+ to $\Lambda(1520)$ production from CLAS is more than a factor 50 lower than the value claimed by SAPHIR Group. Thus the SAPHIR result is completely negated.

The CLAS Collaboration repeated the study of the exclusive reaction $\gamma d \to nK^+K^-p$ [63]. The integrated luminosity of the new data is about a factor 30 higher than that of the previously published CLAS paper on the same reaction, where a $4.6\,\sigma$ significant $\Theta^+ \to nK^+$ signal was claimed [24]. In the new data no signal was observed. The CLAS Collaboration re-examined its earlier work, using a background shape based on new data (see Fig. 12), and concluded that the background level in the earlier sample had been underes-

timated and that the signal (now with only $3\,\sigma$ significance) was probably a statistical fluctuation.

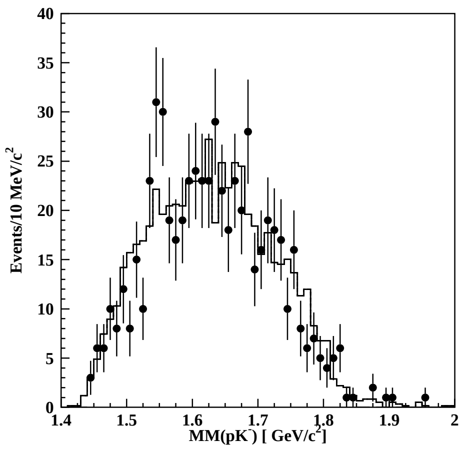

Figure 12: *Comparison of the previously published* [24] *CLAS result (points) with the new* [63] *CLAS result (histogram) normalized to get the same total number of counts.*

The COSY-TOF Collaboration repeated the experiment studying the $pp \to pK^0\Sigma^+$ reaction with substantially improved statistical accuracy and extended detection capability [64]. For the new measurement a slightly higher beam momentum was chosen ($3.059\,\mathrm{GeV}/c$ instead of $2.95\,\mathrm{GeV}/c$) to make the mass spectrum more regular in the region of the expected Θ^+ signal. No evidence for a narrow resonance in the pK^0 spectra was found and the upper limit on a cross section $\sigma_{tot,X} < 0.3\mu b$ (95% C.L.) was set for the mass region of 1.50 GeV/c^2 – 1.55 GeV/c^2. It was also concluded that in the previous measurement [30] the background level had been underestimated and that the significance of the Θ^+ signal is much lower than claimed in the previous publication.

In the years 2002–2003 the LEPS Collaboration collected a new data sample of the $\gamma\,d$ and $\gamma\,p$ interactions with a factor 5 increase in statistics [65]. Preliminary results of two analysis were reported. In the K^+K^- detection mode the Θ^+ signal was confirmed in the missing mass spectrum of the K^- with respect to the neutron after correcting for the Fermi-motion (the reaction is $\gamma n \to \Theta^+ K^- \to (nK^+)K^-$). The number of the Θ^+ signal events increased with the luminosity in the correct proportion, however, the significance remained at the $5\,\sigma$ level. In the second analysis the pK^- final state was studied and the Θ^+ signal was found in the missing mass spectrum of the

pK^- with respect to deutron requiring the pK^- mass to be in the $\Lambda(1520)$ mass region (the reaction is $\gamma d \to \Theta^+\Lambda(1520) \to \Theta^+(pK^-)$). The claimed significance of the peak is $4 - -5\,\sigma$. The background shape is determined by two different methods, however one has to introduce additional peak to describe the missing mass spectrum. Thus, the background shape might be still not well understood. These results of LEPS are in disagreement with negative CLAS results [62, 63], however the two experiments have different acceptance. In 2006 the LEPS experiment started a new run, in which a further increase in statistics by a factor 10 is expected. The data taking should be finished by summer 2007. The new LEPS data might clarify the question of agreement with CLAS.

The Belle Collaboration searched for the charge exchange reaction $K^+n \to \Theta^+ \to pK_S$ using the kaon interactions in the detector material [66]. This reaction provides a model independent information on the width of the Θ^+ and allows to directly compare the result with that of the DIANA Group [5]. No signal was observed at Belle. An upper limit on the Θ^+ width $\Gamma < 0.64\,\mathrm{MeV}$ for the Θ^+ mass $M = 1.539\,\mathrm{MeV}/c^2$ was set, to be compared with the estimate $\Gamma = 0.9 \pm 0.3\,\mathrm{MeV}$ made from the DIANA signal [6]. The upper limit is mass-dependent, going as high as 1 MeV for some values between 1520 and $1550\,\mathrm{MeV}/c^2$, as shown in Fig. 13. The Belle upper limit is conservative, since

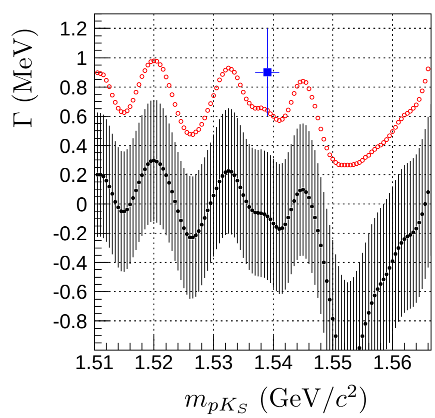

Figure 13: *Belle results for the Θ^+ yield, expressed in terms of the resonance width (black dots). The open dots correspond to the upper limit at the 90% C.L.. The square with error bars indicates the estimate made from the DIANA signal.*

the Θ^+ can be produced also in inelastic KN interactions which are considered as background in the Belle analysis.

The DIANA Group continued the investigation of the charge–exchange reaction $K^+\mathrm{Xe} \to K^0 p\,\mathrm{Xe}'$ [67]. The statistics was almost doubled, however, the momentum distribution of the incident K^+, p_{K^+}, in the new data was shifted to higher values compared to the previous publication [5]. To compare the old and new data samples, DIANA applied a requirement $p_{K^+} < 530\,\mathrm{MeV}/c$, which was automatically fulfilled for the old data. With this requirement the total statistics increased by a factor 1.6, while the Θ^+ yield increased from 29 to 54 ± 16, thus, even by a larger factor than the statistics. Further reduction of the p_{K^+} interval to $445 < p_{K^+} < 525\,\mathrm{MeV}/c$ resulted in the Θ^+ yield of 57 ± 15.

It was found that the Θ^+ signal is concentrated in a narrow momentum interval, $445 < p_{K^+} < 525\,\mathrm{MeV}/c$ (see Fig. 14). The fact that the Θ^+ peak is

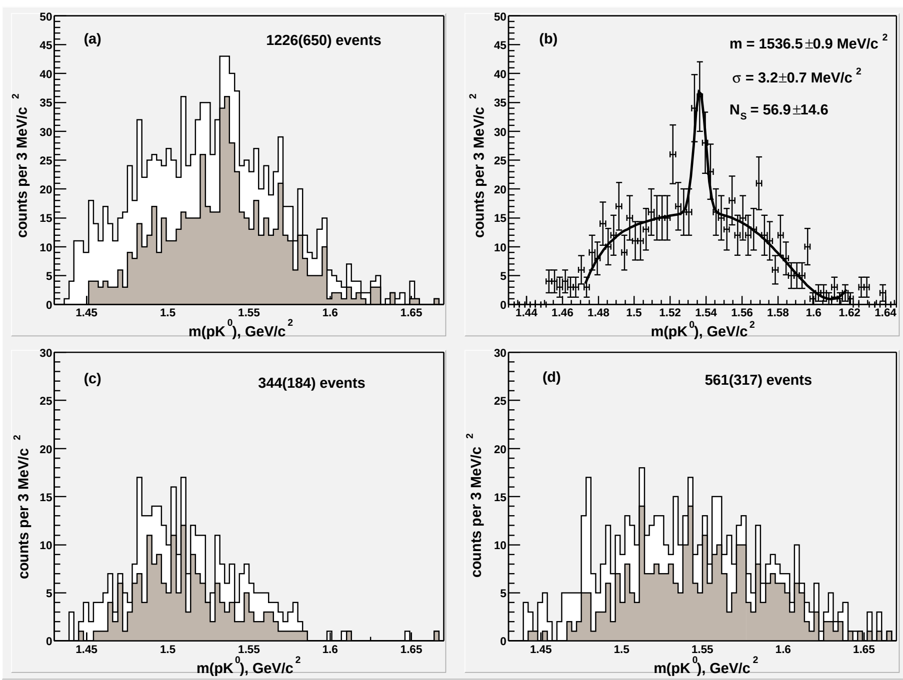

Figure 14: *Effective mass of the K^0p system at DIANA* [67] *for* $445 < p_{\mathrm{beam}} < 525$ *MeV/c (a),* $p_{\mathrm{beam}} < 445$ *MeV/c (c), and* $p_{\mathrm{beam}} > 525$ *MeV/c (d). Shaded histograms are for the selections* $\Theta_p < 100°$, $\Theta_K < 100°$, *and* $\Phi > 90°$. *Shown in (b) is a fit of the shaded distribution in (a) to a Gaussian on top of a fifth-order polynomial.*

not found for $p_{K^+} > 525\,\mathrm{MeV}/c$ was unexpected for the authors of this review.

At Belle [66], the expected Θ^+ yield for $p_{K^+} > 525\,\mathrm{MeV}/c$ is roughly the same as for $p_{K^+} < 525\,\mathrm{MeV}/c$. This follows from the MC simulation, which was verified by tagged kaon data. Based on the p_{K^+} spectrum of DIANA and Fermi-momentum spectrum of xenon nucleus, we find that the Θ^+ yield at DIANA in the $p_{K^+} > 525\,\mathrm{MeV}/c$ interval should be about 30% of the Θ^+ yield in the $445 < p_{K^+} < 525\,\mathrm{MeV}/c$ interval. Thus, about 17 additional events with Θ^+ should be seen at DIANA in the $p_{K^+} > 525\,\mathrm{MeV}/c$ interval. Given the background level at DIANA, the absence of the Θ^+ signal there corresponds to about $2.5\,\sigma$ downward fluctuation.

The new estimation of the Θ^+ width performed by DIANA is $\Gamma = (0.36 \pm 0.11)\,\mathrm{MeV}$, which is extremely small. Diakonov *et al.* conclude that with such a small width the Θ^+ can not be produced in the photoproduction experiments and thus all the positive evidences from such experiments can not be correct [69]. Also the Θ^+ evidence from the analysis of the K^+d cross section [19] – [23] is negated by such a small value of the Θ^+ width.

The NOMAD Collaboration searched for the Θ^+ production in the $\nu_\mu N$ interactions [70]. The Θ^+ signal was not observed and an upper limit on Θ^+ production rate of $2.13 \cdot 10^{-3}$ per neutrino interaction (90% C.L.) was set. Preliminary NOMAD results, quoting the Θ^+ signal with a $4.3\,\sigma$ significance [34], suffered from an incorrect background estimation. The results reported in [34] were obtained using harder proton identification requirements which yielded an increase in the proton purity from 23% to 51.5% with about a factor six loss in the statistics. It is interesting to compare the NOMAD result [70] with the analysis of old bubble chamber neutrino experiments which provide an estimation of the Θ^+ production rate as large as $\sim 10^{-3}$ events per neutrino interaction [26]. As shown in Fig.15, for a large fraction of the x_F range, except in the region $x_F \approx -1$, such a value is excluded.

The most significant Θ^+ signal to date is from SVD-2 Collaboration, which considerably increased the statistics and was able to confirm its earlier observation of the Θ^+ production in the proton nucleon interactions [71]. The statistical significance of the Θ^+ signal at SVD-2 is at the level of $8\,\sigma$. The SPHINX experiment, which operated exactly in the same environment, found null result [47]. It was claimed, however, that at SVD-2 the Θ^+ is produced with very small x_F, while SPHINX has no acceptance in this region. Still, it is not clear how to reconcile the SVD-2 positive result with the null result of the HERA-B Collaboration [46], which was obtained for the same reaction, with the same acceptance in x_F but with the center-of-mass energy 40 GeV instead of 12 GeV. The SVD-2 yield ratio $\Theta^+/\Lambda(1520) = 8 - 12\%$ is in marked disagreement with the upper limit from HERA-B, $\Theta^+/\Lambda(1520) < 2.7\%$ (95% C.L.). The CDF upper limit $\Theta^+/\Lambda(1520) < 3\%$ (90% C.L.) [49] is also applicable

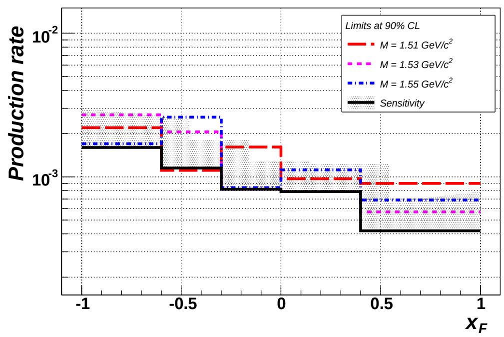

Figure 15: *Sensitivity and upper limits at 90% C.L. for* Θ^+ *production rates at NOMAD* [70] *as a function of* x_F*, for* Θ^+ *masses of 1510, 1530, 1550* MeV/c^2.

here, since for the central production the difference in the nucleon-nucleon center of mass energy should not be important.

To conclude, we would like to cite a paragraph from the Particle Data Group review on pentaquarks (edition 2006) [72]: "To summarize, with the exception of SVD-2, there has not been a high-statistics confirmation of any of the original experiments that claimed to see the Θ^+; there have been two high-statistics repeats from the Jefferson Lab that have clearly shown the original positive claims in those two cases to be wrong; there have been a number of other high-statistics experiments, none of which have found any evidence for the Θ^+; and all attempts to confirm the two other pentaquark states have led to negative result. The conclusion that pentaquarks in general and the Θ^+ in particular, do not exist, appears compelling." Two more negative results (COSY-TOF, Nomad) appeared since the PDG2006 conclusion was made.

The existence of such a large number of results which were subsequently not confirmed demonstrates the importance of the psychological factor in the analysis, especially if the available statistics is low.

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